AD-A114 016 ELECTRO MAGNETIC APPLICATIONS INC DENVER CO F/G 4/1
ATMOSPHERIC ELECTRICITY HAZARDS ANALYTICAL MODEL DEVELOPMENT AN--ETC(U)
JUN 81 J D ROBB F33615-79-C-3412
UNCLASSIFIED EMA-81-R-21-VOL-2 AFWAL-TR-81-3084-VOL-2 NL

1 of 1
AD A
114016

END
DATE
FILMED
5-82
DTIC

AFWAL-TR-81-3084, Volume II

ATMOSPHERIC ELECTRICITY HAZARDS ANALYTICAL MODEL DEVELOPMENT AND APPLICATION

VOLUME II: SIMULATION OF THE LIGHTNING/AIRCRAFT INTERACTION EVENT

John D. Robb
Lightning and Transients Research Institute

Electro Magnetic Applications, Inc.
P.O. Box 26263
1978 South Garrison Street
Denver, Colorado 80226

August 1981

Final Report for Period August 1979 - June 1981
Approved for public release; distribution unlimited

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Donald A. Hirst

DONALD A. HIRST, ILT
Project Engineer

Gary A. DuBro

GARY A. DuBRO, Chief
Atmospheric Electricity Hazards Group
Flight Vehicle Protection Branch
Vehicle Equipment Division

FOR THE COMMANDER

SOLOMON R. METRES
Director
Vehicle Equipment Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/FIESL, *W-PAFB, OH 45433 to help us maintain a current mailing list".*

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) ATMOSPHERIC ELECTRICITY HAZARDS ANALYTICAL MODEL DEVELOPMENT AND APPLICATION VOLUME II SIMULATION OF THE LIGHTNING/AIRCRAFT INTERACTION EVENT	5. TYPE OF REPORT & PERIOD COVERED Technical-Final August 1979-June 1981
	6. PERFORMING ORG. REPORT NUMBER EMA-81-R-21-VOL-2
7. AUTHOR(s) John D. Robb	8. CONTRACT OR GRANT NUMBER(s) F-33615-79-C-3412
9. PERFORMING ORGANIZATION NAME AND ADDRESS Electro Magnetic Applications, Inc. P.O. Box 26263 Denver, Colorado 80226	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 24020212
11. CONTROLLING OFFICE NAME AND ADDRESS Flight Dynamics Laboratory (FIESL) Air Force Wright Aeronautical Laboratories Wright-Patterson Air Force Base, Ohio 45433	12. REPORT DATE June 1981
	13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lightning	Nonlinear
Simulation	Aircraft
Testing	Assessment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this report, a review of currently used lightning test techniques for aircraft is given. The requirements for lightning simulation are given and discussed. Finally, a new approach for simulating the lightning/aircraft interaction is presented, and is based on nuclear electromagnetic pulse (NEMP) technology.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

FOREWORD

This report is the final report under Subcontract SC-79-003 with Electro Magnetic Applications, Inc. (EMA) of Denver, Colorado. The subcontract is part of an overall contract to EMA from the USAF Flight Dynamics Laboratory, Contract No. F33615-79-C-3412, to improve the state of the art of atmospheric electrical indirect effects on aerospace vehicles. It was to include: (a) an improved definition of the lightning channel, (b) improved test methods for indirect effects testing of complete aircraft and (c) improved analysis of indirect effects coupling to aerospace vehicles. This report covers Phase (b), a study of improved ground test facilities for indirect effects testing on full size aircraft.

LTRI personnel taking part in the studies and report preparation included J.D. Robb, J.H. Larson and E.M. Stai.

Monitoring the LTRI subcontract for EMA and contributing to the studies under their Phase (c), improved coupling analysis, were Drs. R.A. Perala and F.J. Eriksen of EMA.

Also contributing to the studies were Professors M. Uman and P. Krider in providing data (also under a subcontract with EMA from Phase (a)) on the improved channel model characteristics.

This report is Volume II of a three volume set of reports. The other two volumes are:

1. Volume I: "Atmospheric Electricity Hazards - Analytical Model Development and Applications," Martin A. Uman and E. Philip Krider.

2. Volume III: "Electromagnetic Coupling Modeling of the Lightning/Aircraft Interaction Event," by R.A. Perala, F.J. Eriksen, and T.H. Rudolph.

In this report, the salient features of the lightning environment which should be simulated are reviewed. Then a review of the past lightning simulation techniques is presented. Specific Considerations and Requirements for simulation are then presented. Finally, a new simulation approach is presented.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

1. INTRODUCTION

Advanced technology aircraft utilize flight critical and mission critical microelectronics and increasing amounts of composite skins which make then inherently much more susceptible to damage and upset from atmospheric electrical hazards. To improve the state of the art technology and better assess the suceptibility/vulnerability of these advanced technology aircraft, a three phase program has been undertaken for the USAF Flight Dynamics Laboratory which includes:

a. Improved arc channel models of natural lightning

b. Generation of improved ground based test methods

c. The development of improved electromagnetic interaction and coupling codes developed from nuclear electromagnetic pulse analysis for predicting the lightning EM penentration into aircraft circuitry.

This report presents the results of Phase (b) of this program, the development of improved ground based test facilities. Phase (a) a of this program has been carried out by Professors M. Uman and P. Krider and staff and Phase (c) of the program has been carried out by Dr. R. Perala and staff, who also had the overall responsibility for the program through a prime contract with the USAF Flight Dynamics Laboratory.

2. NEW DATA

A new study of the natural lightning phenomena to which aerospace vehicles are subjected, by Weidman and Krider (Ref. 1) and Uman, Krider and Clifford, Ref. 2), has indicated much faster current rise times (30 to 100

nanoseconds) in the many phases of the natural lightning discharge including stepped leader, dart leader, K changes, the return stroke and restrikes as illustrated in Figure 1. These faster rise times have also been confirmed in measurements by Baum, et.al., (Ref 3) and by Pitts (Ref. 4) in a NASA Flight Research Program.

To evaluate properly the lightning strike susceptibility of these advanced designs, new improved simulators are required which have the faster current rates of rise recently discovered in natural lightning and the strong electric fields which are not reproduced in most present high current type lightning simulators. The use of existing nuclear electromagnetic simulators modified to provide both the fast rising currents and radial E fields found in the in-flight environment is suggested for ground tests of new aerospace vehicle designs.

3. LIGHTNING MECHANISMS RELATED TO INDIRECT EFFECTS

It must be recognized that lightning phenomena are extremely complex with current waveforms having an almost infinite variety of waveshapes and with probably great differences in the actual channel characteristics at different altitudes and air densities.

For example, the higher altitude lightning strike current waveforms recorded in an Air Force thunderstorm program (Ref. 5) are different than the current waveforms recorded by the many investigators measuring currents in strokes to ground. The intra-cloud strokes often had relatively low rates of rise and decay in the order of milliseconds and few of the strikes had current peaks over five thousand amperes. These intermediate currents are of great significance in terms of puncture of aircraft fuel tank skins but

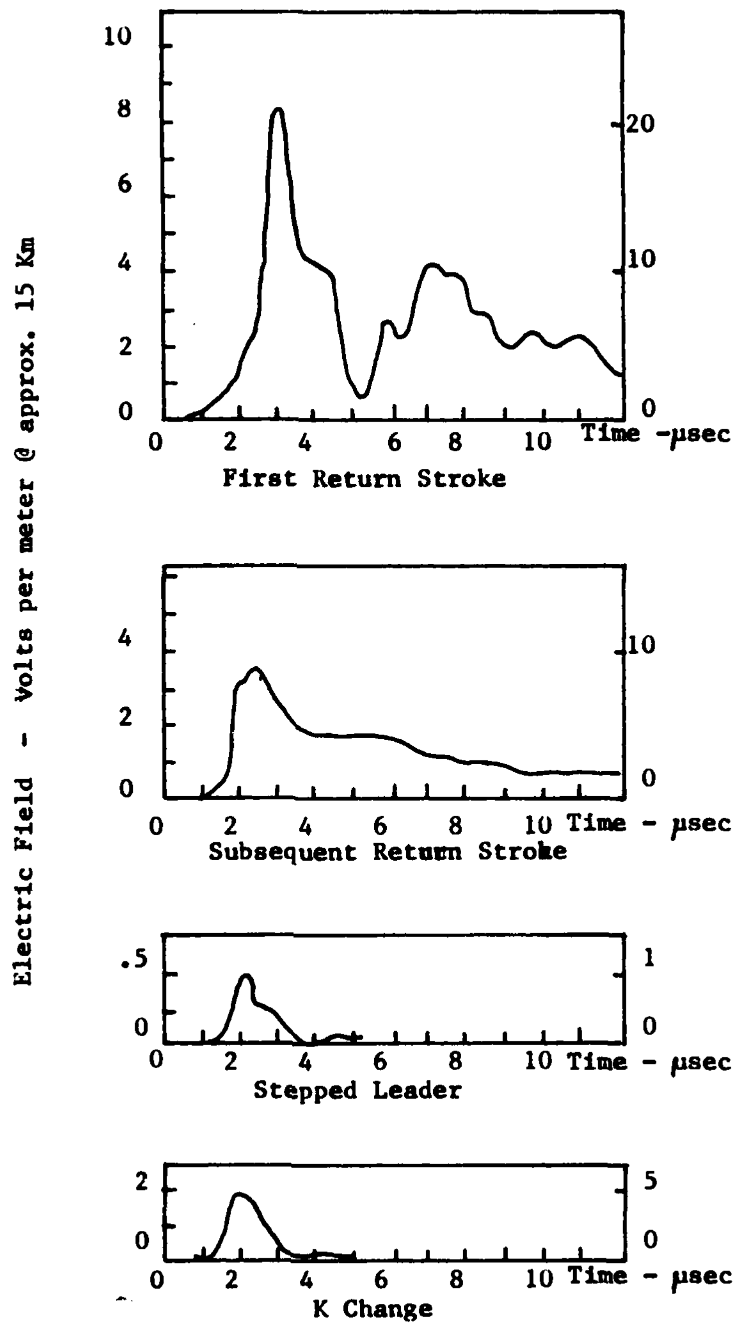
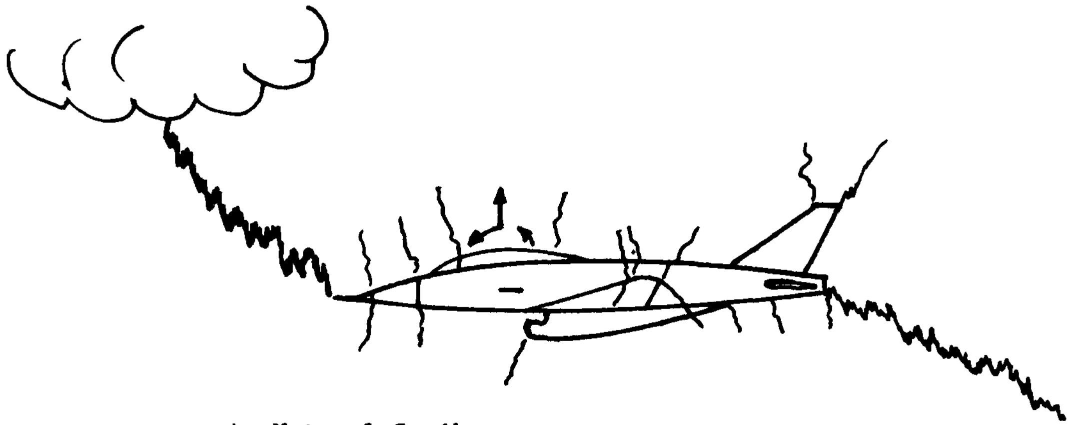


Figure 1. Typical Electric Field Waveforms with Estimated Currents Show Maximum Risetimes of the Order of 100 Nanoseconds. (Ref. 1,2,&3)

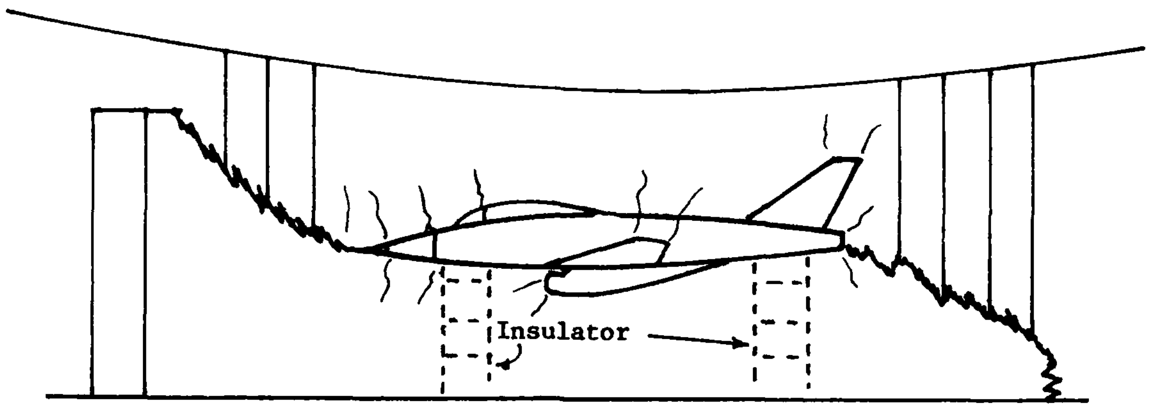
apparently have a much reduced effect on avionics which are more susceptible to the high rate of rise phenomena. The high rate of rise phenomena can, of course, occur in intra-cloud discharges such as K changes as reported in Ref. 1 and 2 and illustrated in Figure 1.

For lightning test purposes it would probably be impractical to try to reproduce the actual channel itself with 50 nanosecond risetimes even though it is possible to simulate the step leader process. For example, LTRI early simulated 80 foot lightning channel passage through an aircraft with one microsecond risetimes. This was done using artificial channel stepping to direct the stroke as illustrated in Figure 2.

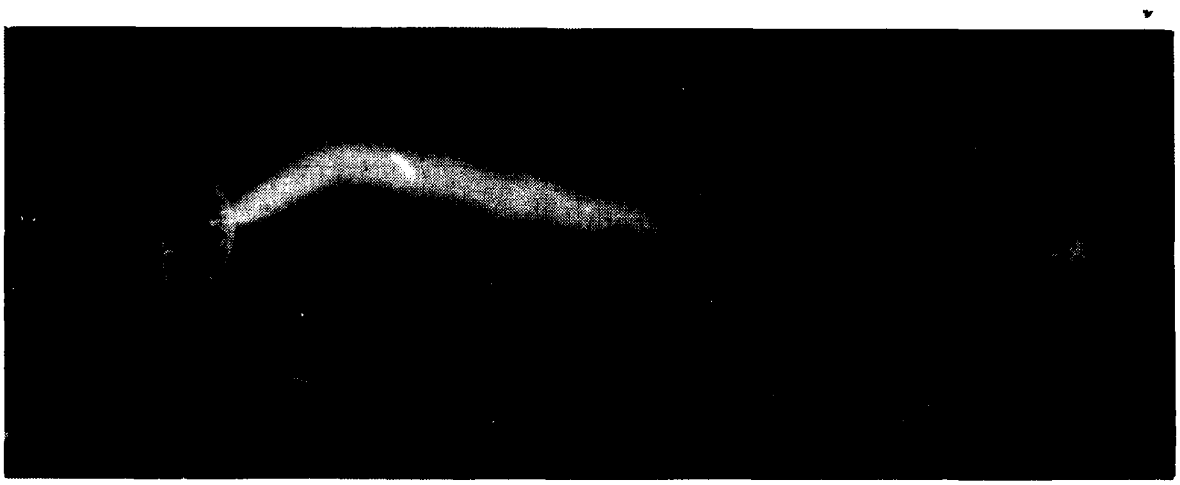
The generally accepted mechanisms of stroke contact and passage through the aircraft may be reviewed in terms of indirect effects which need to be reproduced in simulation systems. As indicated in Figure 3, when the step leader approaches the vehicle, streamering is induced off both the nearby and opposite extremities of the vehicle. The step leader closes with one of the streamers exiting from the vehicle, probably quite rapidly. The final closure is estimated at several microseconds. The vehicle then rises to the potential of the tip of the step leader at which point the streamering increases substantially. Next, one of the streamers from an opposite extremity extends to become the advancing step leader in the discharge passage onto the earth or another cloud region. When the step leader contacts a streamer induced off the earth, the high current return stroke moves back up the channel through the vehicle in effect grounding it to the earth at this point and thereby reducing the potential on the vehicle. The streamering thus tends to collapse back into the aircraft. The high current return stroke passes on through the vehicle into the cloud.



A. Natural Strike

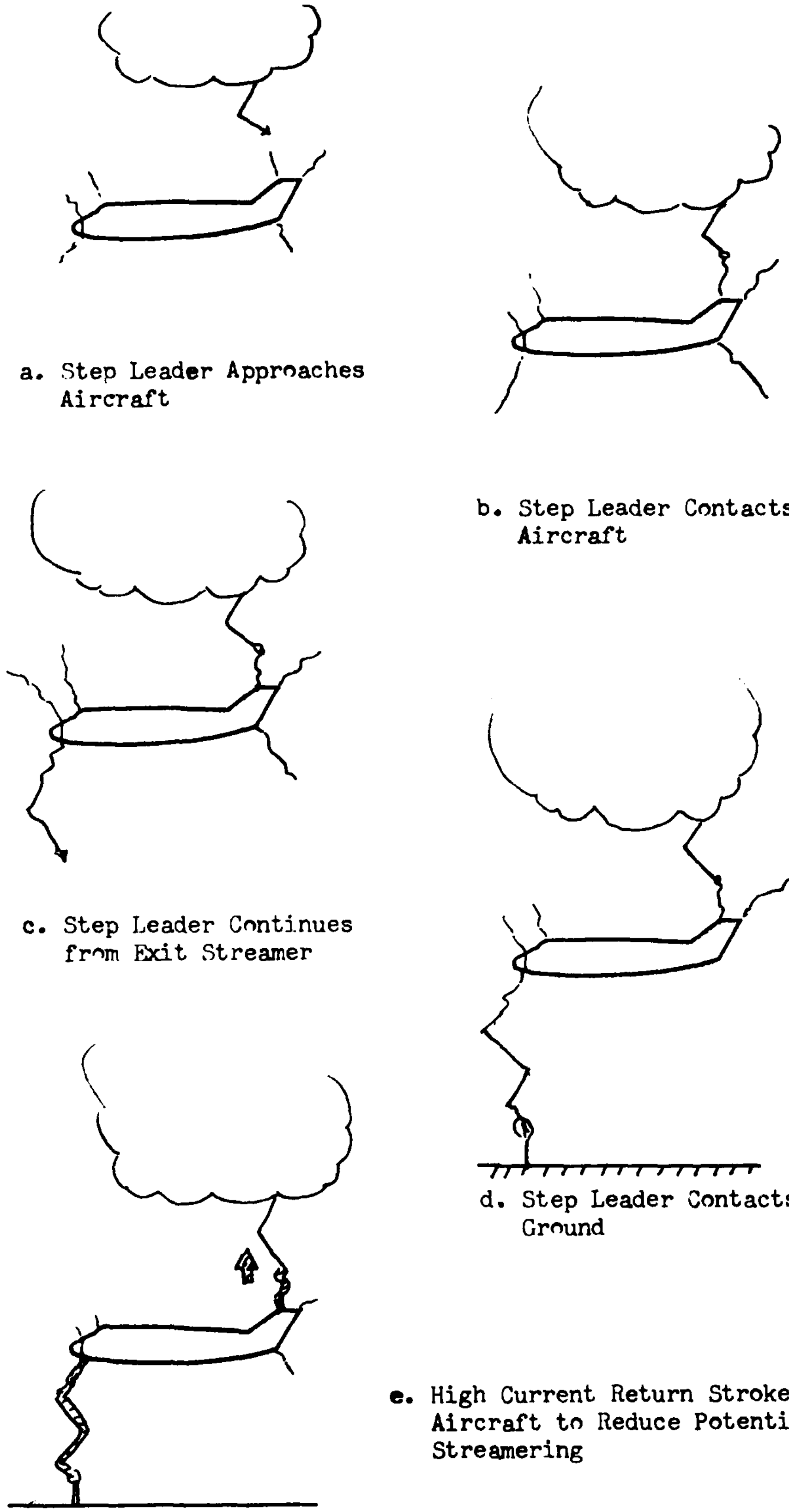


B. Laboratory Strike Simulator



C. Photograph of Laboratory Strike With Artificial (pin cushion) Stepping (60 feet - 5 megavolts)

Figure 2. Laboratory Simulation of In-Flight Stepping Mechanisms



a. Step Leader Approaches Aircraft

b. Step Leader Contacts Aircraft

c. Step Leader Continues from Exit Streamer

d. Step Leader Contacts Ground

e. High Current Return Stroke Passes Through Aircraft to Reduce Potential and Reduces Streamering

Figure 3. Mechanism of Lightning Stroke Contact and Passage Through Aircraft

The high current return stroke is followed by the more slowly rising current of the lower cloud charge regions dumping through the existing channel. This is referred to as the intermediate current and has currents of a few thousand amperes lasting a few milliseconds. These phases of the flash are of less interest as they usually have lower rates of rise. The high current return stroke can then be followed by one or more restrikes with or without DC continuing currents of a few hundred amperes passing through the existing channel.

As was shown in Figure 1, the stepped leader, the first return stroke and the restrikes in intra-cloud discharges can all have transient phases with 50 to 100 nanosecond risetimes.

4. INDIRECT EFFECTS

The above mechanisms produce the following effects of interest in indirect effects simulation: (a) initial E field induced streamering as the step leader approaches the vehicle, (b) a more intense streamering as the step leader contacts the vehicle, (c) streamer collapse as the high current return stroke returns from the earth to partially ground the vehicle through the channel, followed by (d) H fields with high rates of rise about the vehicle as (e) the current I passes through the vehicle and onto the clouds.

The same basic phases would occur in intra-cloud discharges but generally with lower magnitudes as aircraft passage through the interior of a thunderstorm can tap charge regions of relatively low charge. The currents are also lower, but as indicated by Uman, K changes in intra-cloud discharges can still have fast rise times.

As noted, the many types of lightning can have an almost infinite variety of waveforms in addition to the substantial differences that probably exist in the channel as a function of altitude and air density. To reproduce these in any significant detail would be extremely difficult and expensive. Present simulation approaches attempt to reproduce the most critical effects, not the phenomena. These effects are the current and current rate of change, the electric field and electric field rate of change, and the magnetic field and magnetic field rate of change, noted in this report by the symbols I, $\dot{I}$, E, $\dot{E}$, H, $\dot{H}$.

The magnitudes of the various components in natural lightning are indicated in Table I and are tentative because current research is still attempting to determine the distribution of these parameters, most specifically the high current rates of rise. Table I will, of course, always be in the process of modification in terms of new information.

The studies of Uman and Krider on the lightning channel model and the computer coupling modeling of Perala and staff under the separate phases of this contract indicate the magnitudes of currents and fields which need to be simulated in indirect effects testing of full scale aircraft, as follows.

4.1 I and dI/dt

The current waveforms indicated by Weidman and Krider and others (Berger Ref. 6) show a typical steepening of the wavefront near the crest and do not indicate a current rise to a full 200 kiloampere crest in 50 to 100 nanoseconds. A representative value of the fast rising section of the waveform

TABLE I. MAGNITUDES OF NATURAL LIGHTNING PARAMETERS & PROPOSED MAGNITUDES FOR FAST RISE INDIRECT EFFECTS SIMULATOR

		Natural Lightning	Proposed Indirect Effects Simulator
Current	I	200 KA	50 KA
Current Rate of Change	$\dot{I}$	500 KA/μs	500 KA/μs
Electric Field	E	3×10^{6} V/m	3×10^{6} V/m
Electric Field Rate of Change	$\dot{E}$	3×10^{13} V/m	3×10^{13} V/m
Magnetic Field	H	30,000 A/m	30,000 A/m
Magnetic Field Rate of Change	$\dot{H}$	3×10^{11} A/m/s	3×10^{11} A/m/s

would be 50,000 amperes rising in 50 to 100 nanoseconds. This data requires an increase in rate of rise from the old value of 100,000 amperes per microsecond specified for present indirect effects testing to one million amperes per microsecond, a great increase.

4.2 E and dE/dt

The electric field can nearly reach the critical value of 3,000,000 volts per meter at sea level initially and then is reduced as streamers and surface plasmas leave the vehicle surfaces radially to provide shielding.

The streamering from an aircraft surface under extremely high electric fields is illustrated in the early LTRI tests of an aircraft wingtip as illustrated in Figure 4. With a wingtip mounted on top of a Marx impulse generator at peak voltages of about eight million volts, the electric fields were about full scale. The rise time was about one microsecond and the fall time was about 50 microseconds. The streamers extended an estimated 7 to 10 feet into space about the wingtip. The electric field off an object 30 meters above the ground at eight million volts is about comparable to the field off an object 300 meters in the air at a potential of 80 million volts as may be verified by analogy to the gradient off a sphere or ellipsoid at two different heights.

Although the initial connection time of the stepped leader and the induced streamer off the aircraft would begin fairly slowly in a period of time of the order of 5 to 10 microseconds, simple estimates reported in Volume III of this series indicate values of $\frac{\partial r}{\partial t}$ of about 10^{12}.

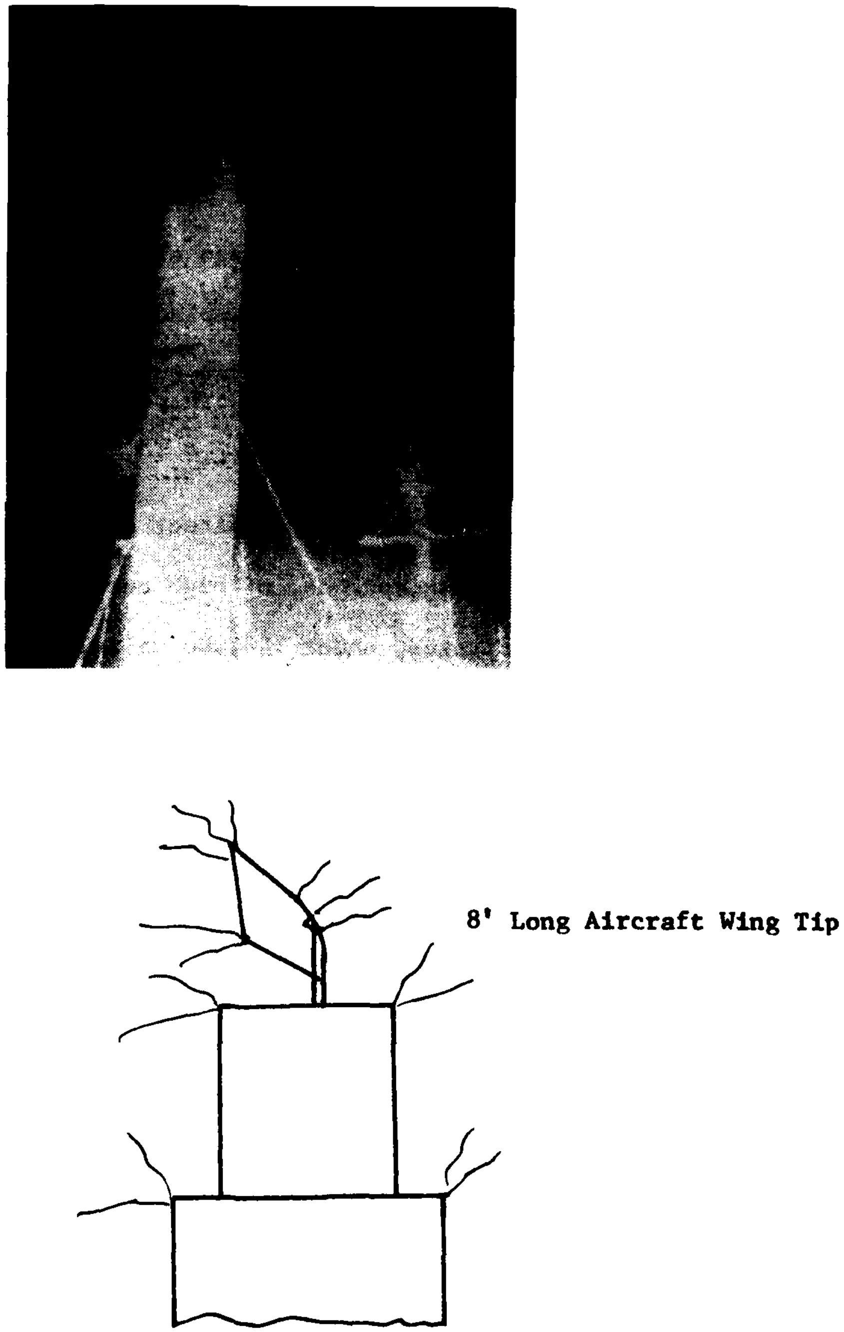


Figure 4. Near Full Scale Streamering Off Aircraft Wing Tip on 7.5 Megavolt Marx Generator

4.3 H and dH/dt

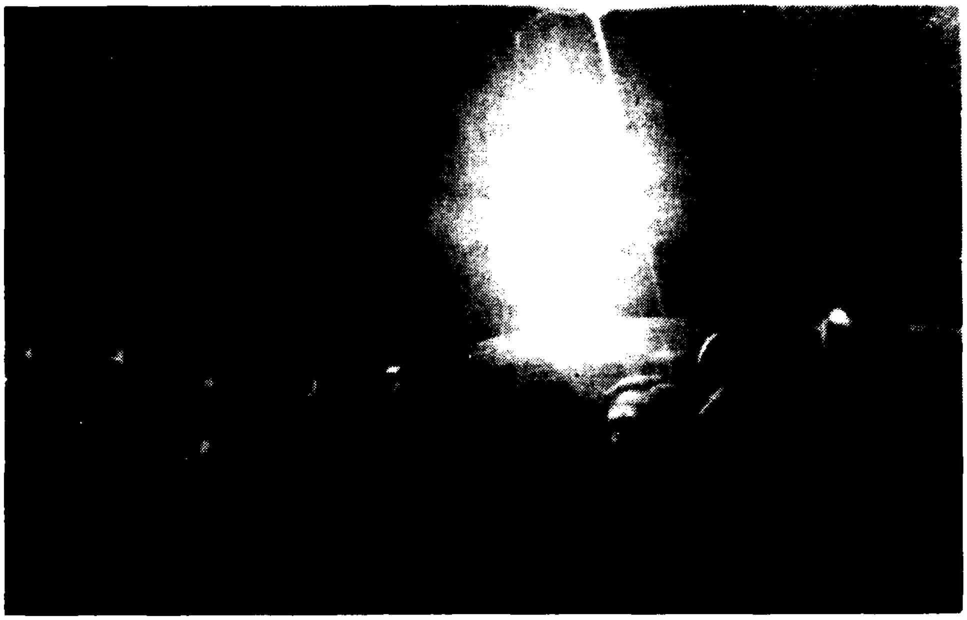
The maximum H field and H field rate of rise correspond to that which would be produced by a fast rising 50,000 current ampere waveform passing through the aircraft being tested. The H field magnitude is approximately equal to the current divided by the fuselage or wing periphery and is more exactly expressed as the solution to the Laplace equation. The H field rate of rise is equal to the H field divided by the current rise time.

5. REVIEW OF PRESENT FACILITIES

The presently available lightning indirect effects test facilities consist primarily, with a few exceptions, of high current generators operating at relatively low voltages, under 150,000 volts, to produce currents rising to crest in 1 to 30 microseconds.

5.1 Early LTRI Facilities

Lightning & Transients Research Institute has carried out full scale indirect effects tests (Newman, Ref. 7 and Shaver, Ref.8,1968) on a range of aircraft from F-104 fighters to large P3A four engine ASW aircraft as illustrated in Figure 5. The tests were carried out by firing five megavolt Marx generators into the aircraft with and without the engines and electrical systems operating and then measuring the internal voltages induced on wiring. Currents up to 50,000 amperes were used. This was about the maximum allowed for operational aircraft which would have to be flown out after the tests, because of the direct physical damage which the higher current and energy levels would cause. The equipment had a maximum current capability of about 100,000 amperes rising in one microsecond. The current levels



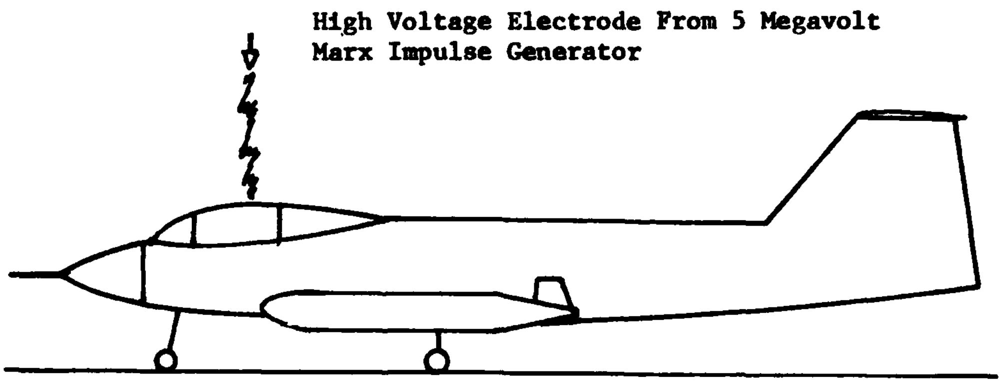


Figure 5. Long Arc To Critical Cockpit Area Applies Both Strong Magnetic And Electric Fields

used, of about 50,000 amperes maximum, were intended to be sufficiently high to cause non-linear effects such as sparking of the doors. The Marx generator was of low inductance design to permit the development of one microsecond rise times through the aircraft which was felt at that time to represent a near minimum rise time for natural lightning.

An underdamped oscillatory waveform was used for the tests. The oscillatory waveform has one advantage over damped waveforms. The measurements of amplitude may be made on the second oscillatory peak after the firing hash on the front of wave has died out. This firing hash is typically found on the front of wave of Marx generators which are connected without internal damping resistances to provide maximum current output. The firing hash was intentionally increased to inject high frequency components into the test waveform and thereby to simulate the higher frequency components believed to exist in the natural lightning channel. The high frequency components can produce more upset in some circuits than the major low frequency driving function.

Measurements were made with shielded oscilloscopes operated inside both fighter and transport aircraft by the technical personnel carrying out the project. Optical triggering of the Marx impulse generators and the oscilloscopes was used to avoid all hard wire connections between the aircraft and the ground except for a single ground point.

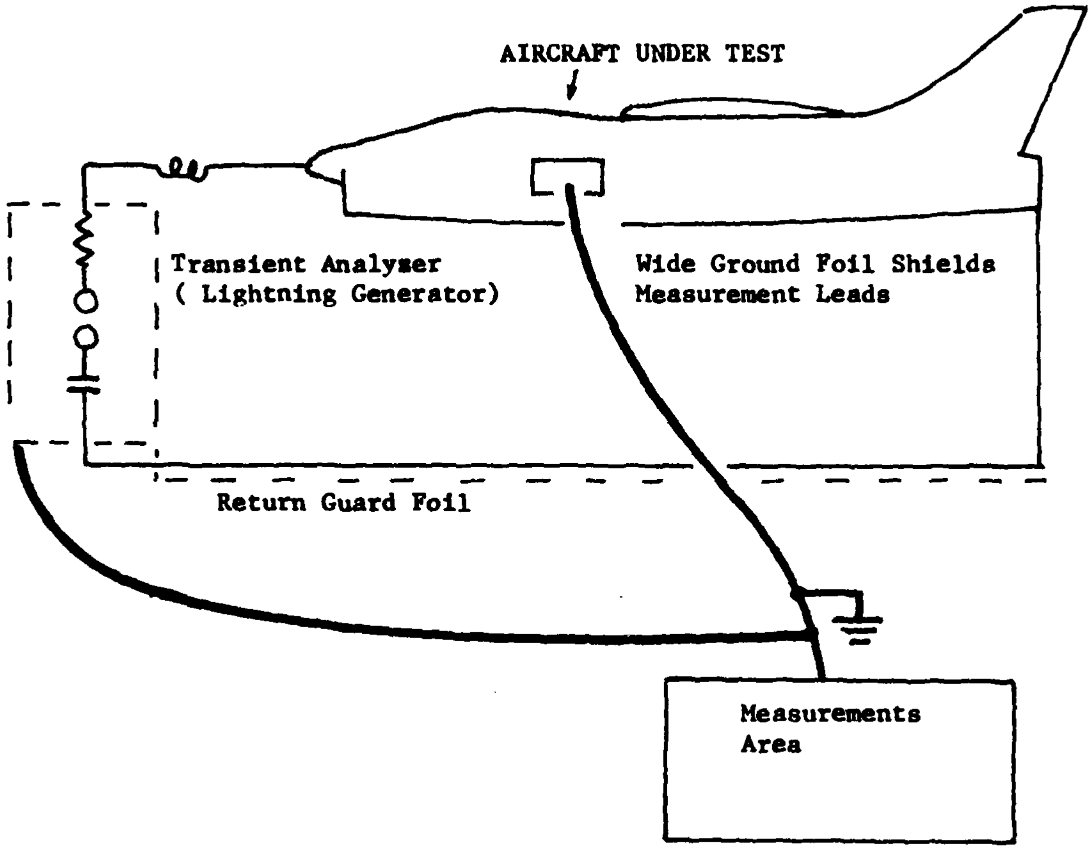
With only magnetic aperture coupling, the internal voltages show a cosine wave. With resistive coupling they show a sine wave. For typical measurements which will show a mixture of the two, the period of the first and second cycles of the damped oscillatory waveform may be compared to

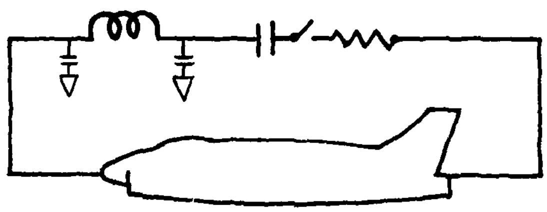
obtain the phase angle from which the mutual inductance and resistance may be calculated. With these coupling parameters, the internal voltages may be calculated for other driving waveforms as the basic mutual inductances are a function of the geometry up to the frequencies at which quasi static theory may be used which for typical apertures of a few feet in diameter are quite high.

Some of the test discharges in the early LTRI tests were fired into the aircraft through long arcs of several meters to simulate the natural lightning contact mechanisms. This provided the strong electric fields in the cockpit area simulating the natural phenomena. It was assumed that the primary coupling mode was magnetic aperture coupling. Electric fields become of more significance with the faster rise times suggested by the new data.

5.2 General Electric High Current Test Technique

The lightning transient analysis technique (LTA) originated at the General Electric High Voltage Laboratory for investigating the transient behavior of power transmission lines, was adapted to study aircraft. The LTA system consisted of a small impulse generator which injected relatively low currents, initially about one kiloampere (Walko, Ref. 9, Hacker and Plumer, Ref. 10) into a vehicle to study the induced voltage and current response as indicated in Figure 6. This technique used a floating high voltage impulse generator. A single ground was provided with a foil sheet which also provided a low impedance path for the balanced measurements cable to the measurements oscilloscope. The advantage of this method was that relatively economical and mobile equipment could be used to run the tests.





Equivalent Circuit

Figure 6. Basic Arrangement of GE-LTA Transient Analyzer Layout (Ref. 13)

This technique provides magnetic aperture and resistive coupling data. It does not provide the effects of non-linearities such as the current flow path changes nor the changes in semiconductor response found at the higher current levels. It may be thought of as a necessary but not sufficient test condition for aircraft verification. But it is certainly a very useful, simple and relatively economical test for determining basic magnetic aperture coupling parameters, which is the fundamental basis for all analysis and protection design. More recently testing has been at higher current levels, of the order of average lightning peak currents.

This method was used on a number of aircraft including an F-89, an F-4 with conventional flight controls and an F-8 with digital flight controls (Plumer et.al., Ref. 11, 12, 13).

This series of tests established the basic approach with consideration of scaling factors, modeling techniques and early hardwire measurement techniques. These test programs also showed clearly for the first time that with twisted pairs of signal cabling in the aircraft and with a single point to ground, only the high frequency reflections of the circuit were measured.

A recent variation of the High Current Test technique by LTI, Plumer and Crouch (Ref. 14) uses a variable parameter transmission line as a driving generator which can provide a wave of increasing steepness near the current peak as seen in natural lightning current waveforms (Berger, Ref. 6). This is achieved with a lumped constant transmission line driver which has varying values of capacity and inductance as shown in Figure 7. The upper current limit of this approach is determined by the voltage capability of the individual capacitor stages.

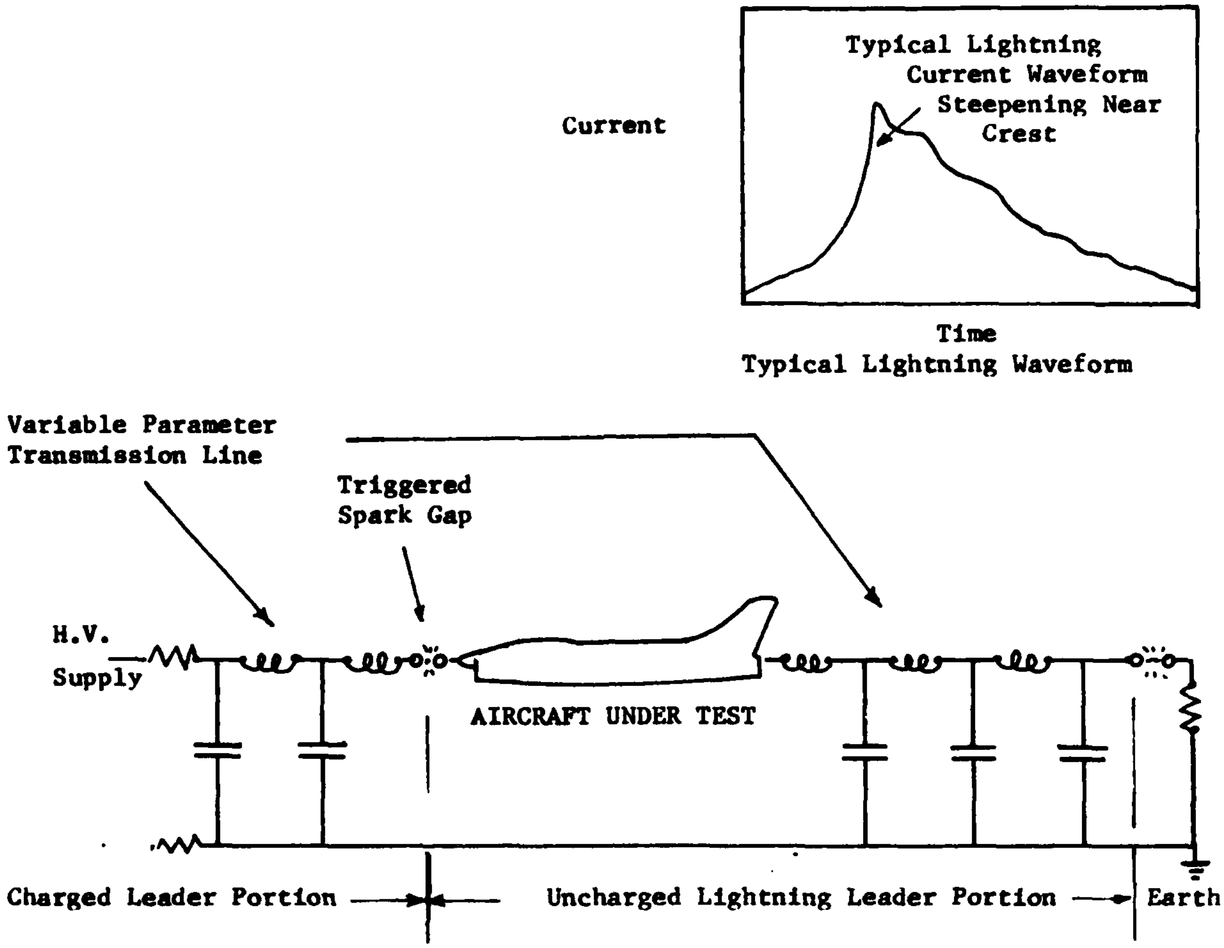


Figure 7. Variable Parameter Transmission Provides Wave Steepening Near Crest to Simulate Natural Lightning (Ref. 14)

5.3 Flight Dynamics Laboratories Expanded High Current Test Technique

The Air Force Flight Dynamics Laboratory added some significant improvements to the basic low level LTA test technique in addition to raising the current level. They used pneumatically controlled gaps to provide a cleaner input waveform (Walko, et.al., Ref. 15). The pnuematic system closes a sphere gap until sparkover occurs and this results in a considerably cleaner waveform than any but the most expensive EMP type switches provide. Also, multiple ground returns were used as shown in Figure 8.

A second major improvement by the Flight Dynamics Laboratory was the introduction of the transient digitizer for measurements in aircraft coupling. This remarkable piece of equipment with its associated computers allows the time domain measurement of the driving function current and the response inside the vehicle which is brought out from the vehicle interior with an optical light pipe. The transient digitizer provides at a push of a key the phase and amplitude spectrums of both the driving and response function and divides the two to provide the actual transfer function. With this approach, the driver system resonances can easily be identified in the driving function spectrum and possible effects on the transfer function can therefore be noted. This is basically an adaptation of the technique which has been used in Nuclear Electromagnetic Pulse testing adopted by the Flight Dynamics Laboratory to Lightning Testing.

The Flight Dynamics Laboratory also sponsored some studies looking at the coupling analysis in terms of the transfer function as a sequential matrix (Ref. 16). The total transfer function was therefore viewed as the product

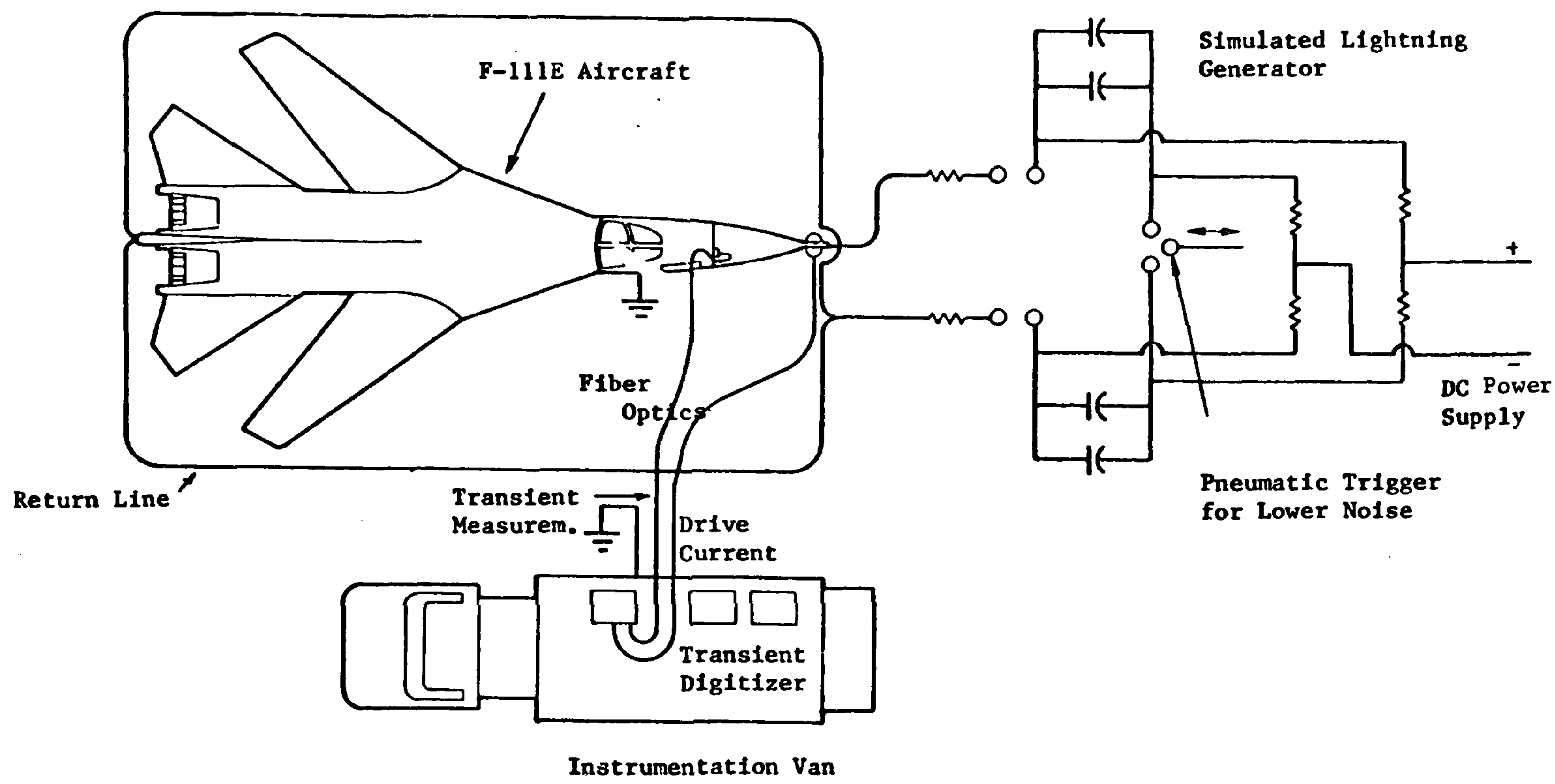


Figure 8. USAF Flight Dynamics Laboratory Adaption of LTA Technique to Provide Cleaner Wavefront, Higher Current (Average Lightning Current Levels) and Improved Measurement Techniques with Transient Digitizers and Fiber Optics Measurements. (Ref. 15)

of the lightning generator to vehicle transfer function, the vehicle to interior transfer function and the interior field to internal conductor transfer function thus permitting correlation of the various phases of the total transfer function. This again is an approach patterned after the techniques introduced by the nuclear electromagnetic pulse community but adapted to the lower frequency spectrum of the natural lightning discharges.

5.4 Culham Laboratories

The Culham Laboratories in England modified this technique to use current return conductors about the periphery of the vehicle in such a way as to reproduce the same current and magnetic field distribution about the vehicle that would be found in flight from lightning current passage (Ref. 17). This approach is illustrated in Figure 9.

A two dimensional field analysis of the fuselage contours was made using the Culham "Potent" computer program, a two dimensional computer solution to the Laplace equation (Ref. 17) and the external return current electrodes were shaped to duplicate this current distribution and magnetic field near the skin.

Another major innovation of the Culham Laboratories was the first use of full scale natural lightning rise times on the basis of the old standards of 100,000 amperes in one microsecond through an entire aircraft fuselage section. Measurements were made of the coupling modes into the fuselage and simplified analysis techniques were developed for determining the cockpit fields and the magnetic field penetration through slot apertures.

A major contribution by the Culham approach was the experimental determination that the magnetic field penetration into the vehicle interior was

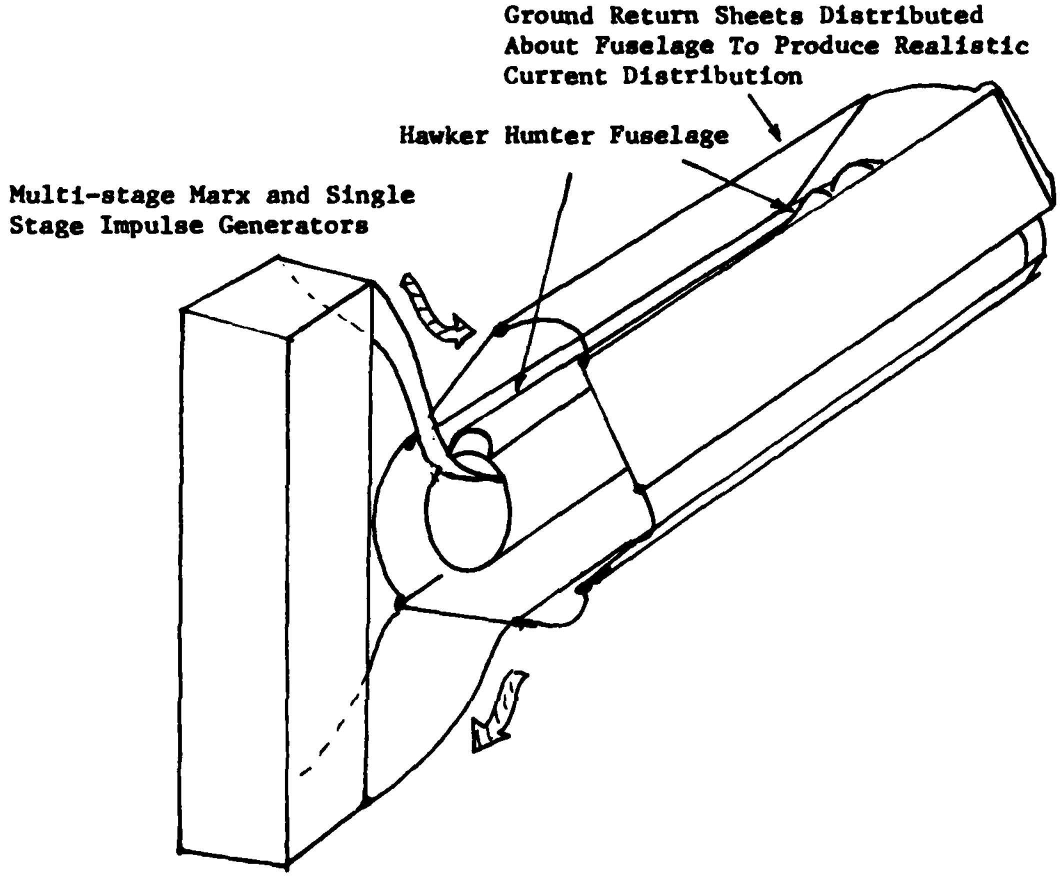


Figure 9. Culham Laboratories Fire First 100 Kiloampere Per Microsecond Discharges Through Aircraft Fuselage (Ref. 17)

extremely slow, of the order of milliseconds, as a result of inductive current redistributions as distinctly contrasted to the diffusion phenomena in which the charge diffuses to the inside of the skin in relatively short times, of the order of ten microseconds in a metal skin. Both phenomena are slower than aperture magnetic field coupling which follows the lightning current waveform.

The Culham Laboratories first identified some major aspects of full size aircraft indirect effects testing. These include the following:

a. Induced voltages are generated by magnetic aperture coupling and are scaled with di/dt max and not with I max.

b. The induced voltages can be calculated on the basis of the airframe current distributions.

c. The key factor in high frequency induced voltages is the noise in the firing switch which suggests that Marx generators are not the best for this type of test. Clean switches such as the laser variety would be optimum for this application.

d. Scaling high frequency response measurements is unreliable with noisy switches.

5.5 McDonnell Douglas Corporation

A different technique was introduced by the McDonnell Aircraft Division (Ref. 18) high voltage laboratory in which high voltage (megavolt) sparks were discharged to an electrically floating cylinder (or an aircraft) to produce the very fast rise times followed by sparkover of the vehicle to ground to provide the slower, high current, short circuit natural resonances of the test circuit. This test technique is illustrated in Figure 10.

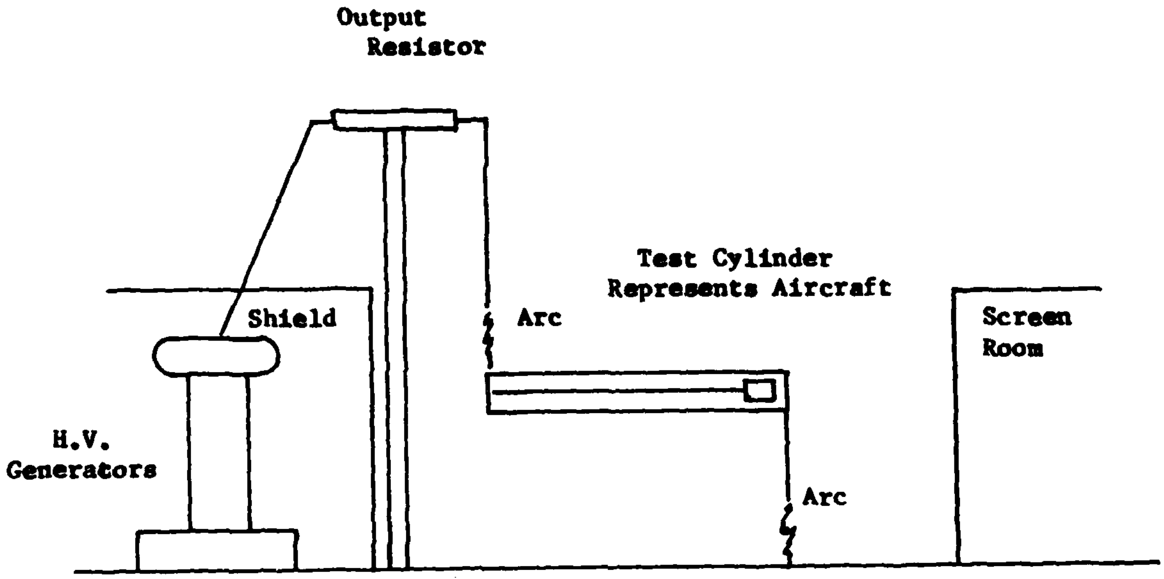


Figure 10. McDonnell Douglas-Dual Arc Excitations System Simulates Several Natural Phenomena

The McDonnell techniques were developed following determination in joint studies with Uman, Krider and Clifford (Ref. 2) of the faster natural lightning current rise times and first recognized need for the faster rise times in indirect effects testing.

5.6 Swept CW Techniques

A different approach has been taken by EMA and Boeing Aircraft Company (Ref. 19); the use of RF excitation of the vehicle to determine the basic RF transfer function which can be then utilized by Fourier techniques to provide the transient response. The RF analysis technique uses a swept frequency signal generator and network analyzer. Its advantage is great simplicity with relatively simple equipment. The tests of a complete vehicle, after it has been setup for running impulse tests with proper return electrodes, can be done relatively quickly with the proper equipment. The ease with which a test can be carried out suggests that it would be advisable to use it for confirming impulse measurements results as a final brief phase of all impulse test programs.

5.7 Sandia Laboratories

The Sandia technique of using multiple high current generators to produce the effect of multiple 200,000 ampere restrikes is of greater significance in terms of direct physical effects on aerospace vehicles and mechanical destruction at entry points which permit subsequent entry of lightning stroke energies. But it does emphasize the possible indirect effects of multiple restrikes. This approach can be adapted to any of the test techniques at the cost of the additional generators and switching systems required to produce the additional restrikes.

5.8 NEMP Lightning Related Developments

Many of the techniques evolved for lightning indirect effects testing such as the use of transient digitizers has been derived from the nuclear electromagnetic pulse community as discussed throughout this report. More recently some of the NEMP groups have published papers on the adaption of NEMP techniques to lightning electromagnetic testing of full size aircraft.

Recently Baum (Ref. 20) has proposed the PARTES concept in which the vehicle is subjected to all the lightning currents and the electric and magnetic fields to which it would be subjected during a strike in flight in correct phase and time sequence. He has also suggested the use of scattering matrix concepts in bracketing the allowable test levels to be used in qualification testing of full size aircraft or subsystems.

6. INDIRECT EFFECTS SIMULATION

In attempting to determine the types and magnitudes of lightning channel components that should be used in simulation testing, it is useful to review the basic coupling mechanisms.

Most present simulators reproduce essentially the magnetic field aperture coupling. High currents flowing in the skin of the vehicle have associated magnetic fields which penetrate through apertures such as windows, skin joints and access doors. Although charge diffusion to the interior skin can result in internal Maxwellian displacement currents and associated internal magnetic fields, the effects are relatively low except for very fast current rates of rise. With the recent data on faster rates of rise, this effect becomes of greater significance but is still below the effects of direct mag-

netic field aperture coupling for most vehicle configurations. Direct low frequency current penetration through the vehicle interior can exist but it can be shown (Robb, Ref. 21) that the rates of rise are extremely low, that the currents are low and that the effects for a metallic vehicle are relatively insignificant except possibly in the area of flammable fuel vapors.

The magnetic fields from the direct current diffusion to the interior surface have been shown (Ref. 21) to be relatively insignificant for metal skin vehicles as the current redistribution times are of the order of milli-seconds resulting in extremely low internal magnetic field rates of rise. Thus for all practical purposes this aspect of magnetic field coupling can be ignored. Conduction through a vehicle interior can be serious. Calculated and measured currents of one-half percent (1000 amperes for a 200 kilo-ampere strike) still can do significant damage to avionics equipment such as digital air data computers.

A major new coupling element suggested by the recent data on much faster current rates of rise is that of electric field aperture coupling. The displacement currents penetrating through an aperture are a direct function of the electric field rate of rise and the overall suggestion of 30 to 100 nanosecond current rise times and associated streamering increases greatly the significance of electric field coupling and advanced simulators must recognize this factor. These mechanisms are all indicated in Figure 11. The above comments apply to metallic aircraft.

The introduction of large areas of non-metallic materials in aircraft skins for advanced aircraft requires a separate evaluation of shielding requirements. In terms of design, the changes are quite significant because

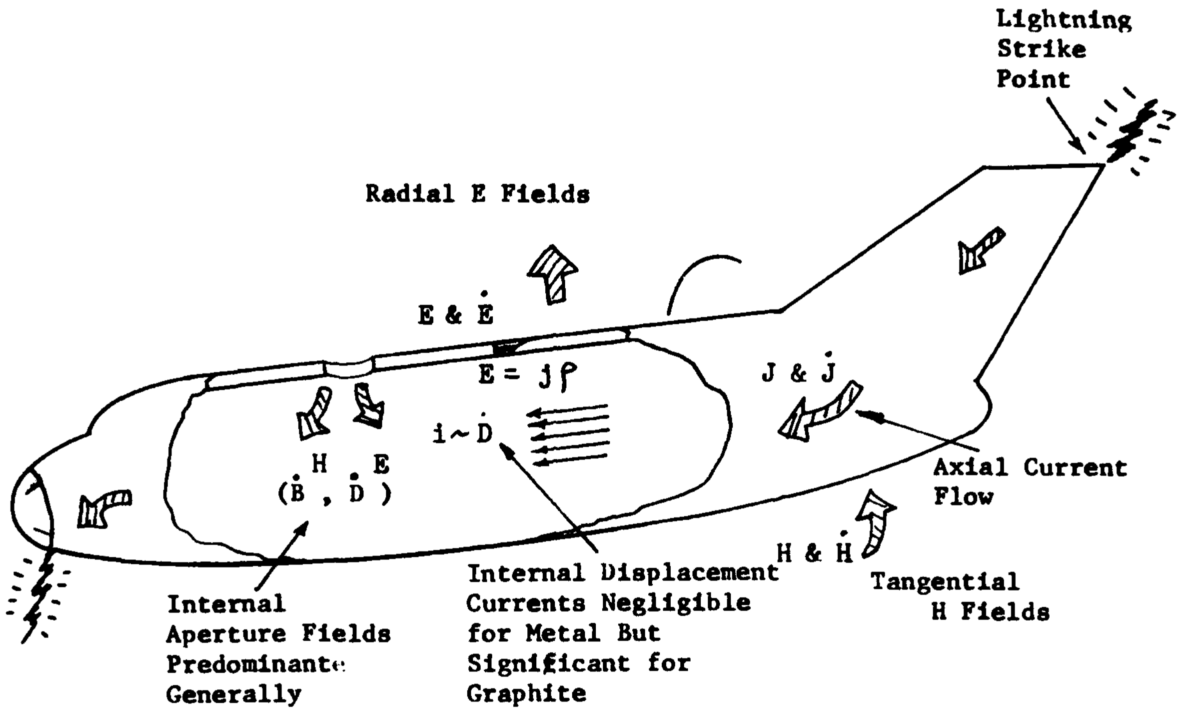


Figure 11. Illustration of Coupling Mechanisms to Vehicle Interior to Be Simulated.

of the greatly reduced skin shielding which requires additional shielding to be either added to the external non-metallic skin portion or into the vehicle interior wiring to supply the additional amount required. In terms of simulation, however, no basic changes are required. The maximum magnitudes of I, $\dot{I}$, E, $\dot{E}$, H, and $\dot{H}$, the currents and electromagnetic fields suggested as the maximums to which an aircraft are subjected in flight during a lightning strike remain basically the same.

One major factor in indirect effects testing, is the question of non-linearities and scaling. The use of full scale discharges into an aircraft for indirect effects testing if used could be highly damaging to the aircraft structure. When damage occurs from each shot, this means that essentially a new section must be used for each individual test and this would increase the cost disproportionately. For this reason intermediate magnitudes corresponding to average lightning discharges are most often used. The question then arises as to the scaling factors.

Scaling factors must recognize the change in current paths with amplitude. Access doors which would not spark at low levels may actually spark at the higher levels thus giving an entirely different current path through the vehicle and a different magnitude of internal magnetic and electric fields. Also the sparks in themselves introduce generally very fast rising discharges which couple high frequency components into the interior which were not present at the lower levels as illustrated in Figure 12.

The semiconductor device non-linearities must be recognized; the fact that the effect on the devices can vary greatly with amplitude. It is not so difficult to predict from a low level test what a device performance will

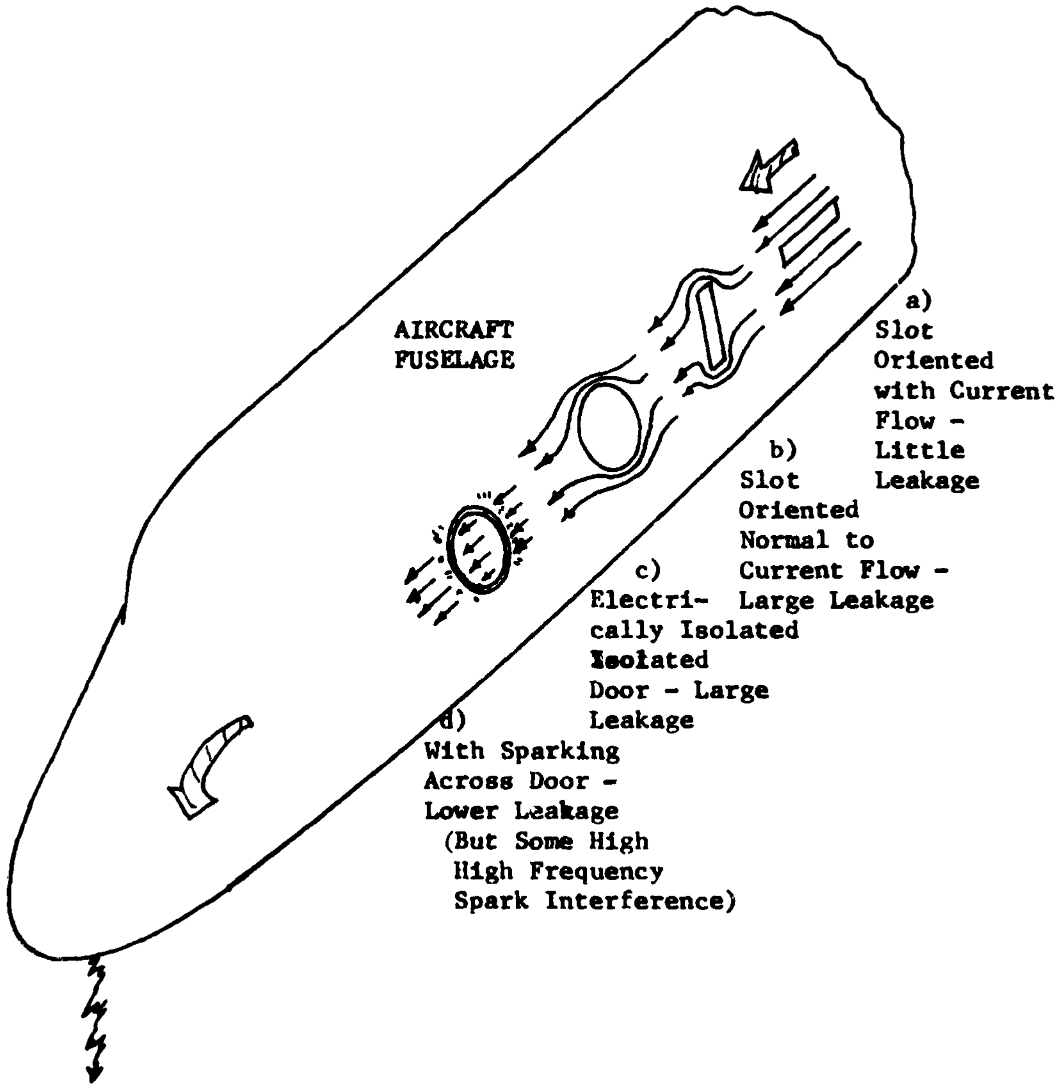


Figure 12. Blockage of Normal Stokes Counter Current Flow Patterns Increase Leakage But Cause High Frequency Spark Interference.

be at high amplitude in terms of non-linearities even for the simpler problem of damage but it is difficult to determine for the problem of overall system upsets.

An additional factor which must be recognized is that the streamering which occurs from the vehicle extremities and also from the edges of the apertures as illustrated in Figure 13 represents a highly non-linear phenomena. What can be done is to provide a simulation system which at least does provide some degree of streamering which can be measured and correlated with in-flight data on advanced in-flight research programs.

Non-linear current flow paths can also occur not only in the external surface of the skin across boundaries such as skin joints but also between the various levels of composite materials such as graphite. It is noted in testing of graphite composites that the current flow paths can vary widely with the waveform of the test current because of the non-isotropic nature of the material and because of the different lay ups. Fast rising currents tend to flow in the exterior due to skin effect and lower rising currents tend to penetrate more deeply. Current flow directions can also change drastically with amplitude and waveshape.

It has been suggested that any types of external skin non-linearities such as spark overs across joints or access doors will actually reduce the electromagnetic field penetration of the vehicle interior permitting current flow closer to normal Stokes counter current shielding patterns than would occur at the lower level where sparks did not occur.

For example, an aperture with an insulating gasket would permit magnetic field penetration at low frequency almost comparable to an open door. The

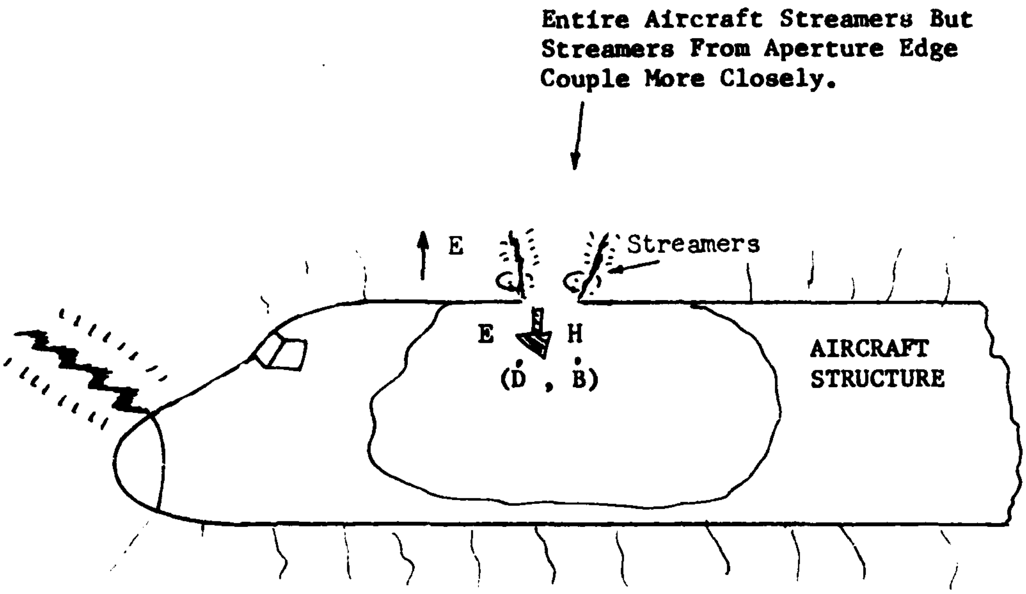


Figure 13. Intense Electric Field From Lightning Stroke Contact Produces Streamer Which Could Couple Magnetic As Well As Electric Fields Into Aperture.

current flow would be around the exterior of the aperture only and thus the magnetic field associated with that current flow would be identical at quasi static frequencies with that if the door were on or off as illustrated in Figure 12. However, with sparkover across the door, the current flow would be through the door and would therefore reduce the magnetic fields penetrating the interior as the current flow would be more analogous to that existing in a continous sheet if the access door were not present. Except for the problem of high frequencies spark generation in the sparkover across the boundaries, this general concept does seem logical but further researches will be required to determine the extent to which it is true.

For the present it can only be stated that there are a number of serious non-linear variations of EM coupling with amplitude and risetime and that for the present it is safe only to assume the worst and at least to extrapolate on the basis of the maximum combined effects of current and current rate of change, and electric field rate of change as appropriate for the particular area or component being tested.

7 ELECTRIC FIELD EFFECTS

One basic concept of lightning indirect effects on aircraft has been that because of the relatively low rates of rise of E field, the Maxwellian displacement currents penetrating through an aperture which are determined by the rate of change of E field, would be relatively low, and that magnetic aperture coupling would predominate. The recent data indicating much faster E field rise times suggests that much greater displace-

ınt currents would penetrate into the interior and that near comparable values
: voltages and currents would be induced on internal wiring from either fast
or H fields. An additional aspect that makes this view of greater import-
ıce is that the nearby electric field disturbances in a thunderstorm occur
ıch more frequently than do actual lightning strikes, probably 100 and 1000
.mes as often as direct strikes. If electric field excitation is significant,
ıis aspect of the in-flight phenomena should be reproduced in an improved
.mulator.

BASIC REQUIREMENTS FOR INDIRECT TESTING

1 General Requirements

Based on the review of the existing technology and the new fast rise ıta, the general requirements for an improved simulator are suggested. It ıst provide (a) a fast rising clean current wavefront to permit better com- ırison of analysis with experimental measurements and (b) an associated ıst rising intense radial electric field.

A review of the literature on aircraft testing indicates that much of ıe current data in the literature is based on oscillograms of the driving ınction which do not have sufficient resolution to permit conclusions as to e high frequency excitation of the internal vehicle circuitry. In simpler rms, the front of wave hash below the resolution of the oscillogram may be imarily responsible for the microsecond response transients if they have lated spectrums as illustrated in Figure 14. Therefore no conclusions can uly be drawn as to the relationship between the driving source and the in- ced voltages measured. This suggests the requirement, therefore, for a ean front of wave on an improved simulator as well as a fast one with high solution measurements.

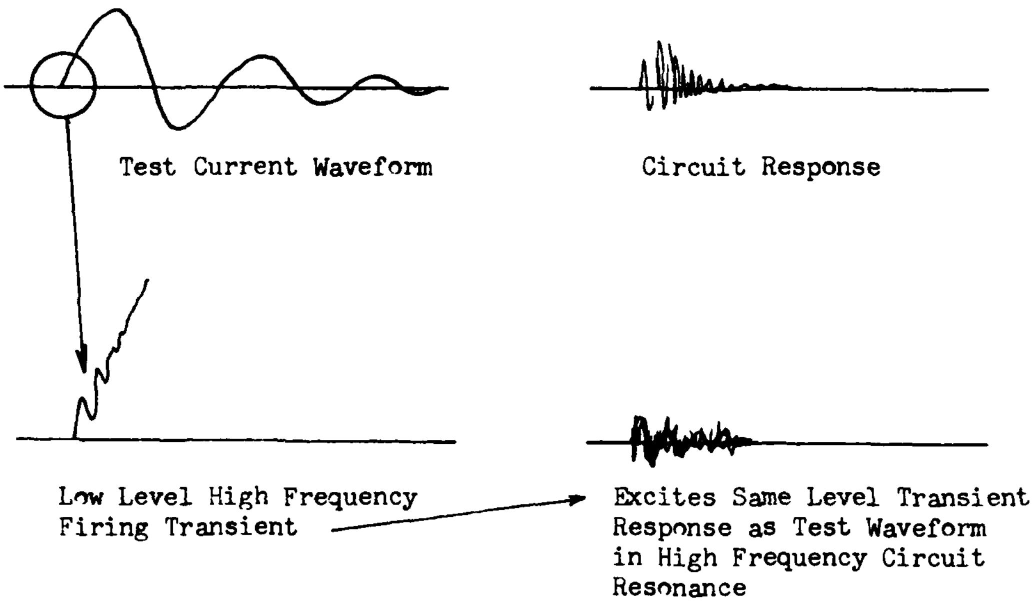


Figure 14. Generator Firing Transient Below Resolution Level of Oscillogram May Cause Predominant Response If Cicuit Being Testing Has Same Resonant Frequency As Firing Transient.

8.2 Lightning Components Needed to be Simulated

The measurement of the fast rise fields in natural lightning strikes in discussions with M. Uman and P. Krider as part of this contract suggests as a minimum the following components which need to be reproduced in an improved test facility.

- Fast and slow E field rates of change associated with the lightning step leader contact and the return stroke passage through the vehicle.
- The fast rising current and associated fast rising magnetic fields simulating step leader, high current return stroke, and K changes.

Based upon these requirements, a specific facility utilizing nuclear NEMP generators has been proposed.

9. PROPOSED NEW SIMULATION APPROACH

The proposed new NEMP type facility is intended only to be used for indirect effects testing of the vehicle avionics and to reproduce the effects, not the phenomena and not necessarily in the proper phase or time sequence. It provides the current, current rates of change, the electric field and electric field rates of change and the magnetic field and the magnetic field rates of change of a natural lightning discharge, (I, $\dot{I}$, H, $\dot{H}$, E, $\dot{E}$.). The high energy and high charge transfers of a natural lightning discharge are not produced as it is not believed that they could contribute significantly to the induced effects on digital electronic equipment except in terms of mechanical damage at entry points which can allow subsequent EM entry. This can best be checked on actual aerospace vehicle hardware mounted on sections of simulated vehicle structure using full scale currents.

The principle of operation of one type of NEMP generator is as follows as illustrated in Figure 15. The Marx impulse generator with its relatively high inductance fires into the peaking capacitor. The voltage rises across the low inductance peaking capacitor until it exceeds the sparkover voltage of the series output gap which is pressurized to shorten the gap and reduce the series inductance into the load. The gap switch fires to give a fast rise output because of its low inductance. It is important in an NEMP system to provide a complete transmission line path from the spark gap switch to the transmission line termination which has a constant impedance so as to minimize reflections and waveform distortion along the line. The line is designed with as nearly a constant geometrical shape as possible to provide a constant impedance. The key elements in the design are the peaking capacitor and the high pressure output switch which have to be designed carefully to withstand the large voltages while maintaining a constant impedance, low inductance output path into the transmission line. The NEMP generator output normally feeds a parallel plate transmission line providing an electromagnetic field in which the test object is immersed. It can also feed various dipole configurations for reproducing the various types of nuclear electromagnetic pulse waveform and field geometries.

The basic concept for lightning use is to use an NEMP type generator which has been demonstrated to produce the clean, fast, controlled front of wave, but slowed down from 10 nanoseconds to between 30 and 100 nanoseconds and directly connected to the aircraft under test. This would be done with a semi-coaxial geometry with the aircraft as the center conductor.

Theory of Operation- Large Marx Generator Discharges into Low Inductance Peaking Capacitor Which Discharges Through Low Inductance Spark Gap into Test Vehicle.

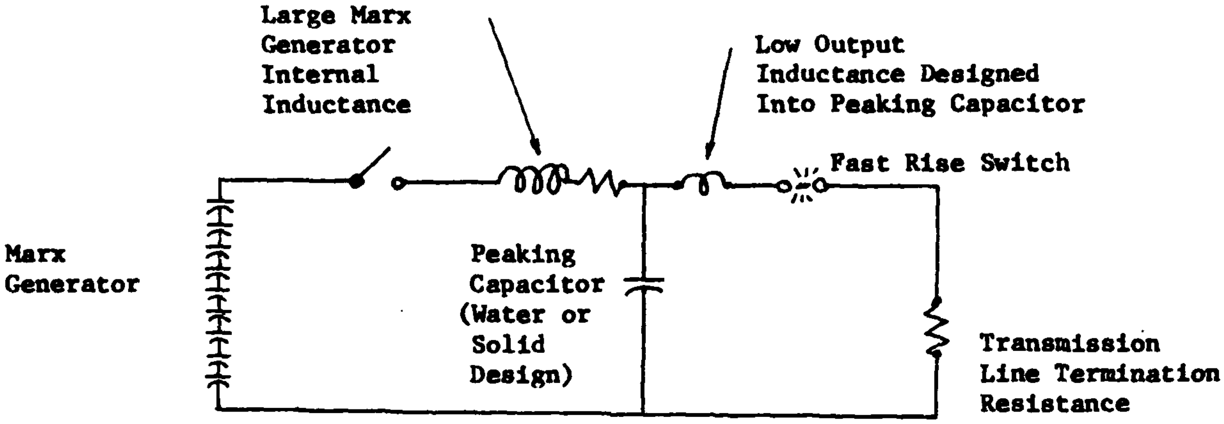


Figure 15. Schematic Diagram of NEMP Generator Circuit Equivalent Circuit.

One problem in aircraft indirect effects testing is the complex geometry which results in complex pulse reflection patterns. In power transmission studies, the regularity of the towers permits the simple generation of a scattering matrix of reflections which can be analyzed in a reasonably simple fashion. However, in aircraft the multiple reflections from both the vehicle complex structure and the complex wiring, present some difficult coupling analysis problems. It is suggested that the use of the fast wavefront for a conducted axial pulse through the vehicle major axes may simplify coupling analysis somewhat by separation in time of the initial pulse front response and the multiple reflections which follows.

As a number of NEMP simulators have been constructed, some are presently available for testing. Also, existing Marx generators can be adapted by use of a peaking capacitor and output spark gap to provide the clean fast front of waves required.

The overall proposed test arrangement is shown in Figure 16. It utilizes a NEMP facility shown at the left, preferably in a shielded configuration (which most of them are), to reduce the radiated signal coupling directly to the vehicle being tested. The output of the Marx generator and peaking capacitor and spark gap is applied directly to the input of the vehicle under test either nose to tail or wing to wing. The output of the vehicle can be connected either to (a) a spark gap to excite the natural vehicle resonances following the McDonnell technique (Ref. 18) or (b) a termination resistor to provide a terminated line and absorb reflections. Individual wire return conductors (cross connected to prevent long wire resonances) are used as they can be adjusted relatively easily to provide appropriate free space current and magnetic field distributions about the vehicle exterior.

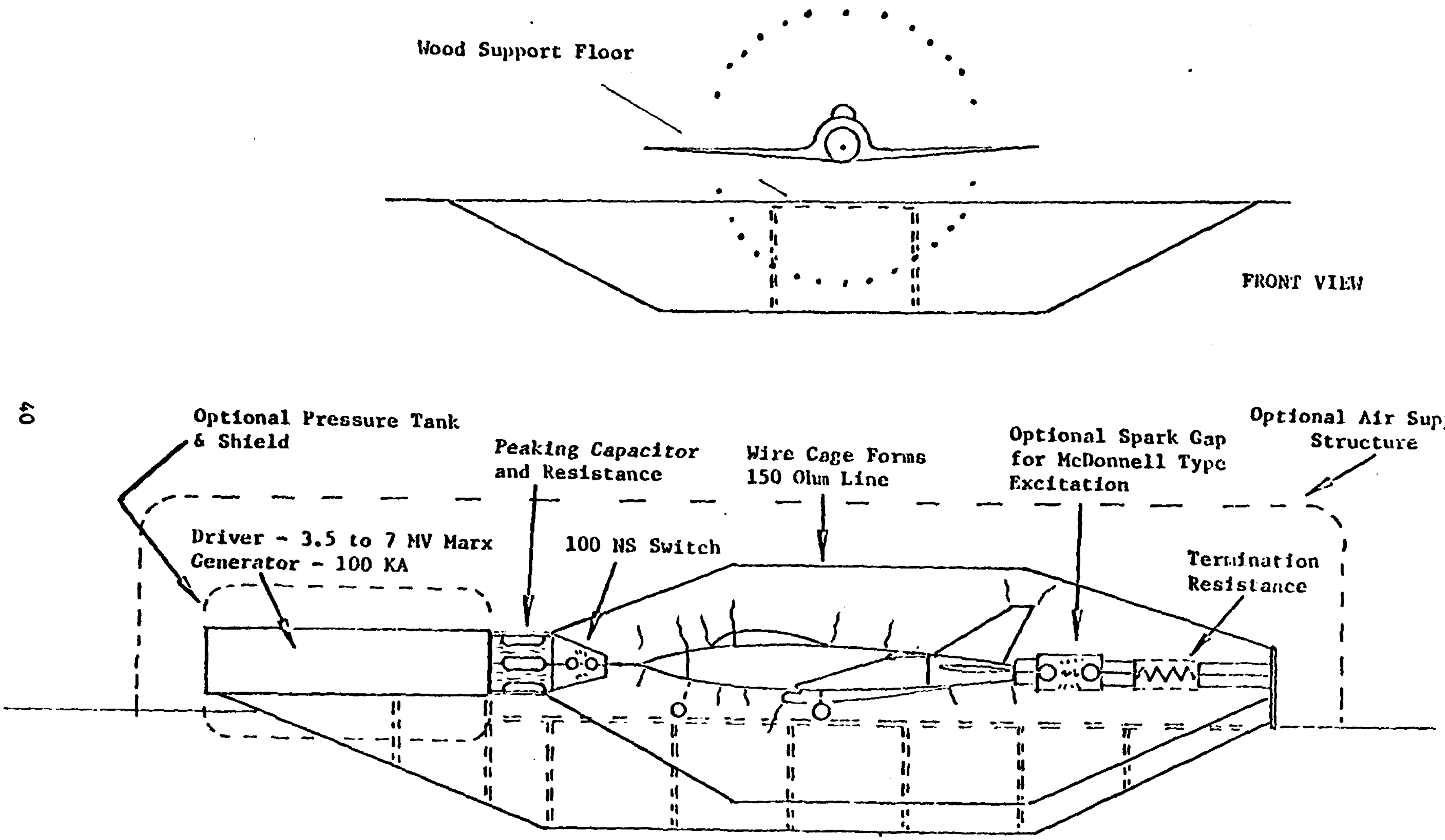


Figure 16. Proposed Test Arrangement for Lightning Indirect Effects Testing of Aerospace Vehicles.

The spacing of the coaxial return wires represents a compromise between the requirements for close spacing to provide minimum impedance and maximum current and the need for wide spacing to permit large streamer development and to cause minimum disturbance of the coupled fields from return conductor images.

An important characteristic of the simulator is that after firing of the input fast rise gap, the vehicle potential rises rapidly to simulate contact of the step leader with the vehicle and causes radial streamering from the vehicle out toward the return conductor grid. This simulates both the electric field coupling from the rapidly changing electric field and the magnetic coupling from the streamer current taking place from the edges of apertures as was illustrated in Figure 13. The streamering is then chopped before it can reach the external grid by use of the downstream chopping gap and this corresponds to the return stroke phase of a natural lightning discharge.

Several phases are proposed for the establishment of fast rise test facilities. These include: (a) the use of existing two megavolt NEMP generators to develop the test techniques without the cost of building a simulator, (b) the construction of a relatively low cost preliminary peaking capacitor and low inductance output spark design for use with the existing Flight Dynamics Laboratory five megavolt Marx generator as an engineering development model and (c) the procurement of a complete system designed specifically for the fast rise LEMP testing based on evaluation of the engineering test model. Some design parameters for these systems are presented in Table II.

TABLE II. NEMP TYPE INDIRECT EFFECTS SIMULATOR DESIGNS

1.	Voltage	Megavolts	2.5	5.0	7.5	10
2.	Line Spacing	Meters	3	6	9	12
3.	Impedance	Ohms	125	175	207	216
4.	Current	Kiloamperes	20	28.5	36	48
5.	Capacity	Microfarads	.01	.03	.03	.03
6.	Decay Time	Microseconds	1	1.5	2	2.5
7.	Peaking Capacitor	Microfarads	.005	.005	.005	.005
8.	Marx Series Resistance	Ohms	10	15	20	20
9.	Marx Inductance	Microhenries	50	70	90	110
10.	Peaking Cap. Induct.	Nanohenries	10	10	10	10
11.	Rise Time	Nanoseconds	50	50	50	50
12.	No. of External Wires		20	24	28	32
13.	Estimated Cost	Kilodollars	100	400	700	1200

Phase (a) would utilize an existing two megavolt NEMP generator for development of the test techniques. This generator has the advantage of being readily available but has the disadvantage of providing too short a pulse duration to develop extensive streamering. It would be used to determine the required techniques for short pulse measurement and for correlation with analytical techniques.

Phase (b) would utilize the Flight Dynamics Laboratory five megavolt generator with a low cost peaking capacity and output spark gap which would utilize the greatly reduced requirements of 50 nanosecond lightning rise time (as contrasted to a 10 nanosecond NEMP waveform) to reduce the cost. A key question to be answered with this engineering model would be the extent of the problems introduced by the lack of shielding of the Marx generator. It is not clear from consideration of the signal to noise ratio aspects whether this would be a problem without tests.

A major goal of this phase would also be to investigate the effects of streamer coupling into the vehicle avionics. In contrast to the small NEMP generator which has too short a waveform duration (less than one microsecond) to feed much in the way of streamers, this larger generator would provide a wave tail of one to five microseconds in duration which could feed substantial streamering. The problem would be to provide substantial streamering to couple interference into the vehicle interior but not sufficient streamering to cross the gap between the vehicle and the return wire grid to short out the impulse generator output. This can be adjusted by adjustment of the output voltage and the downstream output gap.

As seen in Table II, the phase I LEMP generator would provide a two megavolt output with a duration of about 700 nanoseconds. The current into the line would be about 15,000 amperes assuming a 150 ohm transmisson line impedance with a rise time of 50 nanoseconds. The phase II LEMP generator would provide a five megavolt output producing about 35,000 amperes into a 150 ohm line again with a 50 nanosecond rise time. A third alternative would be the use of the full 7.5 megavolts output of the FDL Marx generator into a large peaking capacitor to provide 50,000 amperes with a 50 nanosecond risetime but this would about double the cost.

Preliminary cost estimates indicate a cost of about $100,000 for phase I, $400,000 for Phase II and $700,000 for Phase III. The cost of the commercially built generator procured under multiple bids would probably be somewhat more expensive than the engineering models suggested in this program.

The need for the engineering phase of the program can hardly be overemphasized as evidenced by the difficulties in the development of the NEMP generators built sometimes without sufficient engineering development programs.

The need for rapidly obtaining facilities for fast rise EMP testing can also hardly be overemphasized in view of the rapidity with which sensitive microelectroncis and composite skins are coming into use in advanced aircraft.

10. CONCLUDING COMMENTS

The new proposed facility thus provides the fast rise, clean front of wave high currents at the level of average lightning strikes to aircraft.

This permits easier correlation of the calculated induced voltages with the actual measured voltages by virtue of the clean waveforms. The approach is not intended to reproduce the actual sequence of currents and electric fields existing on an actual aircraft at this time. This would require a number of generators applied at different parts of the vehicle and would increase considerably the cost and complexity of running the test. This represents an initial approach to the PARTES concept of subjecting a test vehicle or component simultaneously to the multiple electromagnetic fields and currents caused by lightning (Baum, Ref. 20) but without the selective EM component phasing which runs up the cost and complexity. It is intended to reproduce only the individual effects of the natural lightning discharge, not the phenomena, and not necessarily in the proper sequence.

REFERENCES

1. Weidman, C.D. and Krider, E,P., "Submicrosecond Rise Times in Lightning Radiation Fields," Proceedings of the Lightning Technology Symposium, sponsored by FAA and NASA at NASA Langley Research Center, Hampton, Va., April 22-24, 1980.

2. Uman, M.A., Clifford, D.W. and Krider, E.P., "A Case for Submicrosecond Rise Time Lightning Current Pulses for Use in Aircraft Induced Coupling Studies," 1979 IEEE Symposium on EMC, San Diego, Ca. Oct. 1979.

3. Baum, C.E., Breen, E.L., O'Neill, J.P., Moore, C.B., and Hall, D.L., "Measurement of Electromagnetic Properties of Lightning with 10 Nanosecond Resolution," FAA-NASA Lightning Technology Symposium Proceedings, Hampton, Va., April 22-24, 1980.

4. Pitts, F.L. and Thomas, E.T., "1980 Lightning Strike Data," NASA Technical Memorandum 81946, NASA Langley Research Center, Hampton, Va., February 1981.

5. Petterson, B.J. and Wood, W.R., "Measurements of Lightning Strikes to Aircraft," Sandia Laboratory Report No. SC-M-67-549, Albuquerque, N.M., January 1968.

6. Berger, K., "Novel Observations on Lightning Discharges - Results of Research on Mount San Salvatore," *Journal of the Franklin Institute* 283, 478-525.

7. Newman, M.M., "General Lightning Protection Review," Proceedings of USAF-SAE 1968 Conference on Lightning and Static Electricity, USAF AFAL-TR-68-290, May 1969.

8. Shaver, H.R., "Lightning Protection Research," Proceedings of USAF-SAE 1968 Conference on Lightning and Static Electricity, USAF AFAL-TR-68-290, May 1969.

9. Walko, L.C., "A Test Technique for Measuring Lightning Induced Voltages on Aircraft Electrical Circuits," Final Report Contract NAS 3-14836, NASA Lewis Research Center, Cleveland, Ohio, January 1973.

10. Hacker, P.T. and Plumer, J.A., "Measurements and Analysis of Lightning Induced Voltages on Aircraft Electrical Circuits," 1970 Conference on Lightning and Static Electricity, SAE-USAF, San Diego, Ca., Dec. 1970.

11. Lloyd, K.J., Plumer, J.A. and Walko, L.C., "Measurements and Analysis of Lightning Induced Voltages in Aircraft Electrical Systems," General Electric High Voltage Laboratory Report HUL 69-161, March 1970.

12. Plumer, J.A., "Lightning Effects Relating to Aircraft, Part III - Measurements of Lightning Induced Voltages in an F4H-1," USAF Avionics Laboratory Report AFAL-TR-72-5 Part III, March 1973.

13. Plumer, J.A., "Lightning Effects on the NASA F-8 Digital Fly-By-Wire Airplane," 1975 Conference on Lightning and Static Electricity, Culham Laboratory, England, April 1975.

14. Plumer, J.A., "Development of Improved LTA Techniques," Private Communication 1980.

15. Walko, L.C. and Schneider, J.C., "Full Scale Lightning Test Techniques," 1980 Symposium on Lightning Technology, NASA Conference Publication 2128, April 1980.

16. McCormick, W., Maxwell, K.J. and Finch, R., "Analytical and Experimental Validation Technique of the Lightning Transient Analysis Technique," USAF Flight Dynamics Laboratory, Technical Report AFFDL-TR-78-47, November 1977.

17. Burrows, B.J.C., Luther, C. and Pownell, P., "Induced Voltages in Full Size Aircraft at 1011 A/s," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa., August 2-4, 1977.

18. Clifford, D.W., Zeisel, K.S., "Evaluation of Lightning Induced Transients in Aircraft Using High Voltage Shock Excitation Techniques," 1979 IEEE EMC Symposium Proceedings, San Diego, Ca., October 9-11, 1979.

19. Young, D.E. and Pisyker, L.D., "The Use of CW Test and Analysis Techniques in Lightning Vulnerability Assessment of Aircraft Systems," 1978 FAA And Georgia Tech Workshop on Grounding and Bonding.

20. Baum, C.E., "Simulation of Electromagnetic Aspects of Lightning," 1980 FAA-NASA Lightning Technology Symposium Proceedings, Hampton, Va., April 22-24, 1980.

21. Robb, J.D. and Chen T., "Analysis and Measurements of Low Frequency Lightning Component Penetration Through Aerospace Vehicle Metal and Graphite Skins," 1980 Symposium on Lightning Technology, NASA Conference Publication 2128, April 1980.

APPENDIX I

**Bibliography
of
Lightning Indirect Effects Simulation
for Full Size Aircraft**

"LIGHTNING INDIRECT EFFECTS TESTING"

Baum, C.E., Moore, C.B., et. al., "Measurement of Electromagnetic Properties of Lightning with 10 Nanosecond Resolution," NASA CP-2128/FAA-RD-80-30, April 1980.

Baum, C.E., "Simulation of Electromagnetic Aspects of Lightning," NASA Lightning Technology Symposium Proceedings, Hampton, Va., 22-24, April 1980.

Bevensee, R.M., Miller, E.K., Deadrick, F.J., and Okada, T.T., "Validation and Calibration of the LLL Transient Electromagnetic Measurement Facility," University of California Research Report S2224, 3 March 1977.

Bishop, J.J. and Simon, M.F., "The Impulse Generators at Les Renardieres,"

Burrows, B.J.C. "Induced Voltages, Measurement Techniques and Typical Values," 1975 Lightning & Static Electricity Conference Proceedings, Culham Laboratory, England, 4 April 1975.

Burrows, B.J.C., Luther, C., and Pownall, P., "Induced Voltages in Full Size Aircraft at 10(11)9 A/S," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa, 2 August 1977.

Butters, W.G. and Clifford, D.W., "Lightning Induced Electrical Transient Testing on Aircraft Wiring Systems," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa., 2 August 1977.

Butters, W.G., Murphy, K.P., and Clifford, D.W., "Experimental Resolution of System Resonances Produced by Simulated Lightning Excitation (Paper unavailable at time of publication), 1980 NASA Lightning Technology Symposium Proceedings, Hampton, Va., 22-24 April 1980.

Chen, K.C., "Transient Corona Effects on a Wire Over the Ground," 1980 NASA Lightning Technology Symposium Proceedings, Hampton, Va., 22-24, April 1980.

Clifford, D.W. and Zeisel, K.S., "Evaluation of Lightning Induced Transients in Aircraft Using High Voltage Shock Techniques," 1979 IEEE EMC Symposium Proceedings, San Diego, Ca., 9 October 1979.

Clifford, D.W., Butters, W.G., Lauber, R.J., and Zeisel, K.S.,"Evaluation of Lightning Induced Transients in Aircraft Using the E-Dot, V-Dot, and I-Dot Shock Excitation Techniques," McDonnell Douglas Report No. A 5683, Dec. 1977.

Clifford, D.W., "The Impact of the Total Lightning Environment of Aircraft Flight Control Systems," 1978 IEEE EMC Symposium Proceedings, Atlanta, Ga., 20 June 1978.

Clifford, D.W., Krider, E.P. and Uman, M.A., "A Case for Submicrosecond Rise Time Lightning Pulses for Use in Aircraft Testing," 1979 IEEE EMC Symposium Proceedings, San Diego, Ca., 9 October 1979.

Dijak, J.T., "Simulated Lightning Test on the Navy Airborne Light Optical Fiber Technology (ALOFT) A-7 Aircraft," Technical Report, AFFDL-TR-77-54, June 1977.

Hacker, P.T. and Plumer, J.A., "Measurements and Analysis of Lightning Induced Voltages in Aircraft Electrical Circuits," 1970 Lightning & Static Electricity Conference Proceedings, San Diego, Ca., 9 December 1970.

Hanson, A.W., "Recent Developments in High Current Testing Techniques for Lightning Simulation," 1977 IEEE EMC Symposium Proceedings, 2 August 1977.

Hess, R.F., "Properties of Induced Transients Associated With EM Fields Produced by Lightning or Other Relatively Slow Rise Time EMP," 1978 IEEE EMC Syposium Proceedings, Altanta, Ga., 20 June 1978.

Hollman, B.Z. and Shuler, E.J., "A Compact Damped Sinewave High-Voltage Generator for EMC Testing," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa., 2 August 1977.

James, R.E. and Phillpott, J., "Simulation of Lightning Strikes to Aircraft," United Kingdom Atomic Energy Authority Research Group, Culham Laboratory, Berkshire, 1971.

Kim, D.G., Dubro, G.A., and Tessler, L.P., "Transmission Line Theory Applied to Aircraft Lightning Interactions," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa., 2 August 1977.

Lee, J.J., "High-Voltage High-Frequency Damped Sinewave Pulser for EMP Simulation,"

Mangold, V.L., Blake, C.L., Walko, L.C., "Lightning Strike Susceptibility Tests on the AIM-9 Missile," Technical Report, AFFDL-TR-78-95.

Mangold, V.L., "Analytical and Experimental Validation of the Lightning Transient Analysis Technique," Technical Report AFFDL-TR-78-47, March 1978.

Mangold, V.L., Walko, L.C., "Lightning Transient Research on an F-111B Aircraft," Technical Report, AFFDL-TR-78-1, February 1978.

Martin, J.C., "Marx Generator Design," AWRE Circuit & Electromagnetic System Design Notes, Note 16, Aldermaston, England, June 1973.

Martin, J.C., "Hun Lecture No. 5," AFWL Circuit & Electromagnetic Systems Design Notes, Note 17, High Voltage Generator Design, June 1973.

McCormick, W., Maxwell, K.J. and Finch, R., "Analytical and Experimental Validation of the Lightning Transient Analysis Technique," Technical Report, AFFDL-TR-78-47, March 1978

McDonald, D.F., Benning, C.J., and Brient, S.J., "Subnanosecond Risetime Multikilovolt Pulse Generator," Review of Scientific Instruments, Vol. 36, No. 4, April 1965.

Moriarity, J.J. and Milde, H.I., "Precise Laser Initiated Closure of Miltimegavolt Spark Gaps," Review of Scientific Instruments, Vol. 42, No. 12, December 1971.

Nanevicz, J.R., Bly, R.T., and Adamo, R.C., "Airborne Measurement of the Electromagnetic Environment Near Thunderstorm Cells," 1977 IEEE EMC Symposium Proceedings, 2 August 1977.

Phillpott, J., "Recommended Practice for Lightning Simulation and Testing Techniques for Aircraft," United Kingdom Atomic Energy Authority Report CLM-R163, Issue No. 1, Culham Laboratory, Abingdon, Oxfordshire, OX143DB, England, May 1977.

Pierce, E.T., "Triggered Lightning and Its Application to Rockets and Aircraft," 1972 Lightning and Static Electricity Conference Proceedings, Las Vegas, Nv., 12 December 1972.

Piszker, L.D. and Young, D.E., "The Use of CW Test and Analysis Techniques in Lightning Vulnerability Assessment of Aircraft Systems," presented at FAA/Georgia Institute of Technology Workshop on Grounding and Lightning Protection, May 1978.

Plumer, J.A., "Transient Analysis Testing of Aircraft to Determine the Electrical Effects of Lightning-Pros and Cons of the Technique," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa., 2 August 1977.

Plumer, J.A., "Lightning Effects of the NASA F-8 Digital Fly-By-Wire Airplane," 1975 Lightning & Static Electricity Conference Proceedings, Culham Laboratory, England, 14 April 1975.

Plumer, J.A., "Lightning Effects Relating to Aircraft, Part III-Measurements of Lightning-Induced Voltages in an F4H-1," Technical Report AFAL-TR-72-5, Part III, March 1973.

Pollard, D.A., "A Broadband Electromagnetic Environments Simulator (EMES)," 1977 IEEE EMC Symposium Proceedings, Seattle, Wa., 2 August 1977.

Robb, J.D. and Chen, T., "The Parallel Plate Transmission Line for Lightning Electromagnetic Effects Testing of Electronics Systems," 1978 IEEE EMC Symposium Proceedings, Atlanta, Ga., 20 June 1978.

Shaeffer, J.F., "Aircraft Initiation of Lightning," 1972 Lightning & Static Electricity Conference, Las Vegas, Nv., 12 December 1972.

Stekolnikov, I.S. and Shkilyov, A.V., "The Development of a Long Spark and Lightning," Laboratory of High Voltage Gas Discharge, Moscow.

Uman, M.A., "Comparison of Lightning and a Long Laboratory Spark," 1971 IEEE Conference Proceedings, April 1971.

Uman, M.A., "Spark Simulation of Natural Lightning," 1972 Lightning & Static Electricity Conference Proceedings, Las Vegas, Nv., 12 December 1972.

Vance, E.F., "Direct Voltage and Current Injection," AFWL Sensor & Simulation Notes, Note 205, September 1974.

Walko, L.C. and Hacker, P.T., "A Test Technique for Measurement of Lightning Induced Voltages in Aircraft Electrical Circuits," 1972 Lightning & Static Electricity Conference Proceedings, Las Vegas, Nv., 12 December 1972.

Walko, L.C., Maxwell, K.J., Schneider, J.G., and Serrano, A.V., "Recent Advances in Indirect Lightning Effects Research," 1978 IEEE EMC Symposium Proceedings, Atlanta, Ga., 20 June 1978.

Walko, L.C., and Schneider, J.G., "Full Scale Lightning Test Technique," 1980 NASA Lightning Technology Symposium Proceedings, Hampton, Va., 22-24 April 1980.

Walker, W., "F-14A/AWG-9 Lightning Protection Investigation," Report No. NADC-79013-20, Naval Air Development Center, Warminster, PA 18974, 23 March 1979.

Wallace, B.J., Burrows, B.J.C., et. al., "Composite Forward Fuselage Systems Integration," Technical Report (2 Volumes) AFFDL-TR-78-110, September 1978.

Weidman, D.C. and Krider, E.P., "Submicrosecond Risetimes in Lightning Radiation Fields," 1980 NASA Lightning Technology Symposium Proceedings, Hampton, Va., 22-24 April 1980.

Zeitler, R.T., Droste, C.S., and Dabold, J.L., "A Lightning Protection Program for the F-16 Fly-By-Wire System," 1979 IEEE EMC Symposium Proceedings, San Diego, Ca. 9 October 1979.

"Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware," Society of Automotive Engineers, SAE Committee AE4L, 400 Commonwealth Drive, Warrendale, Pa., 20 June 1978.